INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(54) Title: PASSIVELY COMPENSATED OPTICAL FIBERS
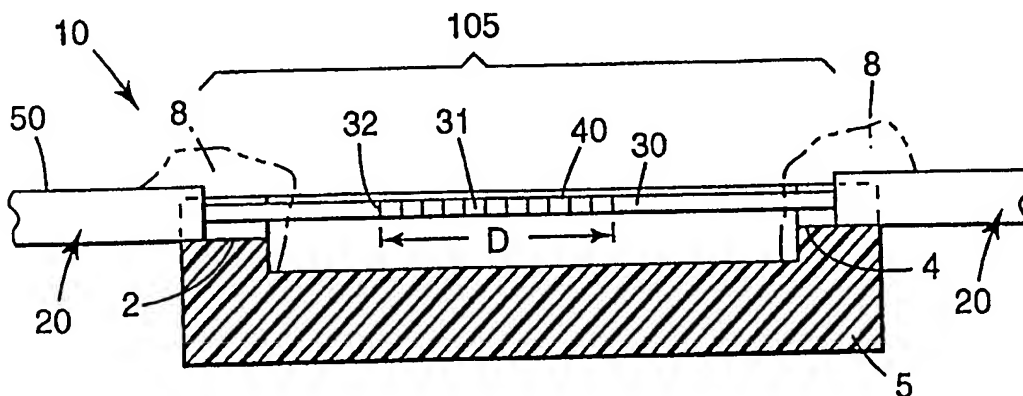
(57) Abstract

A passively compensated optical fiber (20) includes an optical fiber and a support member (5) attached to the optical fiber at a first attachment point (2) and at a second attachment point (4). The distance between the first attachment point and the second attachment point increases with increasing temperature due to expansion of the support member. As temperature changes, support (5) expands, i.e., the distance between first point (2) and second point (4) increases. The expansion creates a strain which is transferred through adhesive (8) to cladding (40), core (30), and LPG (31). The strain transferred to the LPG (31) from the thermally expanding support (5) negates or compensates the central wavelength shift of the long-period grating (31) due to temperature.

PASSIVELY COMPENSATED OPTICAL FIBERS
Background of the Invention

5   The invention relates to optical fibers and long-period gratings.

   Optical fibers are used to guide light which might, typically, be an optical signal used in telecommunications. In general, an optical fiber

10 includes an inner core and an outer clad having an index of refraction less than the inner core. The difference in the index of refraction creates internal reflections forcing the light to propagate along the inner core and preventing it from leaking out of the

15 fiber.

   Some optical fibers include long-period gratings(LPG). A long-period grating is formed by producing a series of perturbations in the index of refraction of the inner core. It is well known in the

20 art how to produce optical fibers having long-period gratings, e.g., as described in U.S. Pat. No. 5,430,817. In general, the optical fibers are made from high purity SiO_2 or other optical materials, e.g., germanosilicate. The long-period gratings can be made

25 by first loading the fibers with hydrogen or deuterium and then selectively exposing the core of an optical fiber to ultra-violet light. Typically, the perturbations are formed by exposing the core through the cladding to an intensity pattern that is produced

30 by transmitting an ultra-violet beam directed through an amplitude mask. The spacing of the perturbations creates a grating characterized by a center wavelength at which light will no longer propagate through the

optical fiber. Long-period gratings with different
perturbation spacings have different center
wavelengths. In general, long-period gratings are
those in which the spacing of the perturbations is at

5   least 10 times larger than the wavelength of input
light. Typically, the period is in the range 15-1500
μm for center wavelengths between 700 and 1500 nm. In
addition, long-period gratings can have a span of
perturbations extending for a few cm.

10   Long-period gratings are used in optical fibers to
filter out selected wavelengths from an optical signal,
e.g., like a notch filter. As an optical signal
propagates through the core and encounters a long-
period grating, specific wavelengths of light, i.e.,

15   the center wavelength of the grating, are converted
from a guided mode of the core to a non-guided mode of
the cladding. A guided mode propagates through the
core of the optical fiber. A non-guided mode of the
cladding dissipates through the cladding and does not

20   propagate through the optical fiber. The center
wavelength conversion from a guided mode to a non-
guided mode is a function of the perturbation spacing
and the difference in the effective index of refraction
between the guided and non-guided mode. Typically, for

25   a single mode optical fiber, there is only one core
guided mode, but several cladding non-guided modes. In
addition, each non-guided mode of cladding is
characterized by an unique effective index of
refraction. Therefore, for a given perturbation

30   spacing, there are several non-guided cladding modes,
and thus, several center wavelengths at which light is
converted from a guided mode to non-guided modes. In
addition, for a given center wavelength, there are

several perturbation spacings at which light is
converted from a guided mode to non-guided mode.

Optical fibers having long-period gratings are
useful as amplified spontaneous emission (ASE) filters,
5   erbium-doped fiber amplifier (EDFA) gain equalizers and
sensors. The use of optical fibers having long-period
gratings continues to increase. Long-period gratings,
however, are sensitive to changes in temperature.
Typically, a central wavelength of 1550 nm shifts by 2
10 to 30 nm per 100°C change in temperature. It is
important, for instance, in telecommunication
applications that the central wavelength of the long-
period grating be constant over temperature ranges of
100°C.

15

Summary of the Invention

In general, in one aspect, the invention features
a passively compensated optical fiber having an optical
20 fiber and a support member. The support member is
attached to the optical fiber at a first attachment
point and at a second attachment point. The distance
between the first attachment point and the second
attachment point increases with increasing temperature
25 due to expansion of the support member.

The passively compensated optical fiber includes a
stainless steel, aluminum, or copper support attached
with an epoxy to the optical fiber at two points. The
epoxy can be ultra-violet curable. The passively
30 compensated optical fiber also includes a coating, an
outer core, and an inner core. The inner core includes
a long-period grating between the first attachment
point and the second attachment point.

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In another aspect, the invention features a method of fabricating a passively compensated optical fiber. The method includes identifying the strain response and thermal response for a long-period grating having a

5 central wavelength, choosing a support member having a coefficient of linear expansion which compensates the optical fiber, and attaching the optical fiber to the support member at a first attachment point and at a second attachment point.

10 In another aspect, the invention features a method of fabricating a passively compensated optical fiber. The method includes calculating an optical fiber design for compensating an optical fiber having a center wavelength and a substrate having a coefficient of

15 thermal expansion, manufacturing an optical fiber having a long-period grating fabricated using the calculated optical fiber design, and attaching the fabricated optical fiber to a support member at a first attachment point and at a second attachment point.

20 In another aspect, the invention features a method of compensating an optical fiber. The method includes providing an optical fiber, attaching the optical fiber at a first attachment point and at a second attachment point, and increasing the distance between the first

25 attachment point and the second attachment point in response to an increase in temperature.

Preferably, the method of compensation is done passively.

The invention provides a passively compensated LPG

30 device by attaching an optical fiber having a LPG to a thermally expanding support.

Brief Description of the Drawing

Fig. 1 is a schematic view of a passively compensated long-period grating device;

Fig. 2 is a plot of the transmission output signal of a passively compensated long-period grating device at 25°C and 100°C;

Fig. 3 is a plot of the center wavelength verses perturbation spacing for coupling between a guided core mode and several non-guided cladding modes; and

Fig. 4 is a plot of the change in the effective index of refraction per change in the effective index of refraction of SiO_2, versus non-guided cladding mode.

Description of the Preferred Embodiments

Referring to Fig. 1, a passively compensated LPG device 10 includes an optical fiber 20 having a core 30, a cladding 40, and a coating 50 for protecting the optical fiber 20. Core 30 includes a long-period grating 31 having a plurality of refractive index perturbations 32 spaced along the central axis of LPG device 10 for a distance, D. A section 105 of the coating 50 surrounding the long-period grating 31 is removed to expose the cladding 40. The exposed cladding 40 is attached at a first point 2 and at a second point 4 to a support 5 with an adhesive 8.

As the temperature changes, the central wavelength of the LPG 31 shifts, e.g., to longer wavelengths. In LPG device 10, strain applied to the LPG 31 by the thermal expansion of support 5 shifts the central wavelength in the opposite direction, e.g., to shorter wavelengths. Therefore, a shift in the central

wavelength due to temperature can be negated or
compensated by applying strain to LPG 31. As
temperature changes, support 5 expands, i.e., the
distance between first point 2 and second point 4

5   increases. The expansion creates a strain which is
transferred through adhesive 8 to cladding 40, core 30,
and LPG 31. The strain transferred to the LPG 31 from
the thermally expanding support 5 negates or
compensates the central wavelength shift of the long-

10   period grating 31 due to temperature.

    The response of the central wavelength to changes
in temperature and strain are used to determine the
amount of applied strain needed to compensate a shift
in the central wavelength. The affect of temperature

15   and strain on the center wavelength is:

$$d\lambda = \frac{d\lambda}{dT} \Delta T + \frac{d\lambda}{d\varepsilon} \Delta \varepsilon$$

(1)

20   where $d\lambda/dT$ is the change in the central wavelength per
change in temperature, referred to as the thermal
coefficient, and where $d\lambda/d\varepsilon$ is the change in the
central wavelength per change in strain, referred to as
the strain coefficient. $\Delta \varepsilon$ is equal to the strain

25   applied to the grating and ΔT is equal to the
temperature change. An optical fiber with a LPG has a
positive thermal coefficient. An optical fiber with a
LPG can have either a positive or negative strain
coefficient. For passive compensation, the optical

30   fiber with a LPG is designed such that the optical

fiber has a negative strain coefficient. The design of
the optical fiber will be discussed in further detail
below. All of the temperature effects (i.e., the
change in the index of refraction of the core and of

5   the cladding as well as thermal expansion of the glass)
are included in the temperature coefficient.
Similarly, all of the strain effects (i.e., the change
in the index of refraction of the core and of the
cladding as well as the change in the spacing of the

10   grating) are included in the strain coefficient.
       The strain and temperature effects are compensated
when there is no change in the center wavelength, i.e.,
when $d\lambda = 0$. Rearranging Eq. 1, compensation is
achieved when

15

$$\frac{d\lambda}{dT}\Delta T = -\frac{d\lambda}{d\varepsilon}\Delta\varepsilon$$

(2)

       Eq. 2 is rearranged to yield:

20

$$-\frac{d\lambda/dT}{d\lambda/d\varepsilon} = \frac{\Delta\varepsilon}{\Delta T} = CTE$$

(3)

       The ratio of the thermal coefficient and the strain

25   coefficient is negative because $d\lambda/d\varepsilon < 0$. Thus, the
left hand side of Eq. 3 is positive and is equal to the
ratio of strain applied to the grating, $\Delta\varepsilon$, per change
in temperature, ΔT. The ratio $\Delta\varepsilon/\Delta T$ is also equal to

the coefficient of thermal expansion (CTE) of a
material. Therefore, compensation occurs when an
optical fiber with an LPG is attached to a support
having a CTE equal to the left hand side of Eq. 3.

5   Referring back to Fig. 1, a passively compensated
LPG device 10 is manufactured from an optical fiber 20
having a 58 micron thick cladding 30 and a 9 micron
thick core 40. The cladding is fabricated from SiO_2 and
the core is fabricated from SiO_2 doped with GeO_2. The
10   effective index of refraction of the core is 1.45 and
the effective index of refraction of the cladding is
1.4446. Core 40 includes a LPG 31 having a plurality of
refractive index perturbations 32 spaced by, 70.5
microns, along the central axis of LPG device 10 for
15   2.5 cm. A 45mm section 105 of coating 50 surrounding
LPG 31 is removed. The thermal and strain coefficients
of optical fiber 20 are measured as 0.048 nm/°C and
-0.0028 nm/microstrain. These values are used in Eq. 3
to determine the CTE value needed for compensation.
20   Optical fiber 20 is attached at a first point 2 10 mm
from one end of LPG 31 and at a second point 10 mm from
the other end of LPG 31. The fiber is attached with a
UV curable adhesive 8, e.g., EMCAST 1060A from
Electronic Materials, located in Breckenridge,
25   Colorado, to an aluminum support 5 having a CTE of 24
microstrain/°C. Adhesive 8, typically, is attached to
the cladding 40 of optical fiber 100 approximately 10
mm from either end of LPG 31.

      Referring to Fig. 2, the center wavelength of
30   stabilized LPG device 10 is monitored as the
temperature is increased from 25°C to 100°C. The
change in center wavelength per change in temperature
is measured as 0.0017 nm/°C. The stabilized LPG device

results in reduction, by a factor of 25, of the center
wavelength's sensitivity to temperature changes.

The support is made of any material, e.g.,
stainless steel, aluminum, or brass, having a CTE which
5   satisfies Eq. 3, for an optical fiber with a LPG having
measured coefficients of temperature and strain. The
range of CTE values, however, is limited to the CTE
values of known support materials. Therefore, a
support material having a CTE equal to the ratio of
10 measured thermal and strain coefficients for an optical
fiber might not exist. In this case, either the
support having the CTE which best satisfies Eq. 3 is
used or an optical fiber with a LPG having a different
perturbation spacing is manufactured. In general,
15 optical fibers manufactured with smaller perturbation
spacing can be compensated by using existing support
materials. For example, assume that one optical fiber
(Fiber A) with a center wavelength of 1800 nm is
fabricated with a perturbation spacing of 100 microns
20 and another optical fiber (Fiber B) with a center
wavelength of 1800 nm is fabricated with a perturbation
spacing of 300 microns. Of the two fibers, Fiber A is
more likely to be compensated by using existing support
material than is Fiber B, because Fiber A has a smaller
25 perturbation spacing.

Whether one can compensate an optical fiber having
a particular perturbation spacing and center wavelength
is calculable. The coefficients of temperature and
strain are affected by the design of the optical fiber,
30 e.g., geometry, materials, and perturbation spacing.
Compensation as defined in Eq. 3, is also related to
the change in the index of refraction of the optical
fiber by:

$$CTE = -\frac{\frac{dn_{SiO_2}}{dT}\left(1-\frac{dn_{effclad}}{dn_{SiO_2}}\right)}{d\lambda/dL}$$

(4)

5   where n_{SiO_2} is the index of refraction of fused silica,
     dn_{SiO_2}/dT is 6.7 X 10^{-6} per °C, and $d\lambda/dL$ is the change
     in the center wavelength per change in the perturbation
     spacing of the LPG. The CTE values of the support
     materials are known, e.g., stainless steel has a CTE

10   value of 11 microstrain/°C. The two remaining unknown
     quantities, $dn_{effclad}/dn_{SiO_2}$ and $d\lambda/dL$, are different for
     each non-guided cladding mode, but they are calculable.
     In addition, there are several non-guided modes for
     which a center wavelength is coupled from a guided

15   mode. Therefore, the non-guided mode having a
     $dn_{effclad}/dn_{SiO_2}$ and $d\lambda/dL$ which comes closest to
     satisfying Eq. 4, for a given center wavelength, is
     chosen.

     The quantities $dn_{effclad}/dn_{SiO_2}$ and $d\lambda/dL$ are calculated by

20   solving an eigenvalue problem which takes into account
     the geometry of the fiber, the index of refraction of
     the core, the index of refraction of the cladding, and
     the index of refraction of bulk SiO_2. The process of
     setting up and solving eigenvalue calculations is

25   similar to the processes described in setting up the
     equations for fiber optic modeling and in solving
     eigenvalue problems found in Monerie, IEEE J. Q.
     Electronics CE-18, p. 535 (1982), and in Snyder and
     Love, <u>Optical Waveguide Theory</u>.

Referring to Fig. 3, the results of the eigenvalue
calculations can be used to generate graphs of the
center wavelength versus perturbation spacing. Each
solid line in the graph represents coupling between the
5   guided core mode and a single non-guided cladding mode.
The non-guided cladding modes are numbered in ascending
order from right to left. The results of the
eigenvalue calculation also can be used to determine
the slope, $d\lambda/dL$, for each non-guided cladding mode.
10 As can be seen from the graph, the lowest non-guided
cladding modes have a positive slope, $d\lambda/dL>0$. Many of
the higher non-guided cladding modes, however, have a
negative slope. The slope, $d\lambda/dL$, is related to the
LPG strain coefficient, $d\lambda/d\varepsilon$, by Eq. 5:

15

$$d\lambda/dE = (d\lambda/dL) \ L$$

(5)

where L is the grating spacing at room temperature, and
20 also represents the change in the perturbation spacing
per change in strain. Therefore, the strain
coefficient is negative when the slope, $d\lambda/dL$, is
negative. Thus, a LPG is designed to have a negative
strain coefficient by fabricating the LPG such that the
25 center wavelength coupling occurs between a guided core
mode and an higher non-guided cladding mode having a
negative slope, $d\lambda/dL<0$.

In addition to the slope, each non-guided cladding
mode also has a $dn_{effclad}/dn_{sio2}$ value. Referring to Fig.
30 4, results from the eigenvalue problem are used to plot
the $dn_{effclad}/dn_{sio2}$ value versus non-guided cladding mode.
Each non-guided cladding mode has a unique set of $d\lambda/dL$

and $dn_{effclad}/dn_{SiO2}$ values. Therefore, for a specific center wavelength, several non-guided cladding mode values are used in Eq. 4 to determine which mode is most effectively compensated.

5   Note that in the embodiments described above, the coating of the optical fiber is removed to transfer strain directly from the thermally expanding support through the cladding and the core to the LPG. A passively compensated LPG device can be made without

10   removing the coating. The optical fiber with coating is attached to a support material. The CTE of the support material needed for passive compensation is calculated by incorporating the strain and thermal responses of the coating into Eq. 3.

15   Although a passively compensated LPG device is described above, an optical fiber having a LPG also can be actively compensated.

Other embodiments are within the scope of the following claims.

What is claimed is:

1.   A passively compensated optical fiber device
(10) comprising:

an optical fiber (20); and

5   a support member (5) attached to the optical
fiber at a first attachment point (2) and at a second
attachment point (4), wherein the distance between the
first attachment point and the second attachment point
increases with increasing temperature due to expansion

10   of the support member.

2.   The passively compensated optical fiber of
claim 1, wherein the support is stainless steel.

15   3.   The passively compensated optical fiber of
claim 1, wherein the support is aluminum.

4.   The passively compensated optical fiber of
claim 1, wherein the support is copper.

20

5.   The passively compensated optical fiber of
any of claims 1 to 4, wherein the support is attached
to the optical fiber at two points with an epoxy.

25   6.   The passively compensated optical fiber of
any of claims 1 to 5, wherein the epoxy is ultra-violet
curable.

7.   The passively compensated optical fiber of
30   any of claims 1 to 6, wherein the optical fiber includes
a coating (50).

8.   The passively compensated optical fiber of
any of claims 1 to 7, wherein the optical fiber
includes an outer cladding (40) and an inner core (30)
having a long-period grating (31).

9.   The passively compensated optical fiber of
claim 8, wherein the long-period grating is between the
first attachment point and the second attachment point.

10.   A method of fabricating a passively
compensated optical fiber comprising:

identifying the strain response and thermal
response for a long-period grating having a central
wavelength,
choosing a support member having a
coefficient of linear expansion which compensates the
optical fiber,
attaching the optical fiber to the support
member at a first attachment point and at a second
attachment point.

11.   A method of fabricating a passively
compensated optical fiber comprising:

calculating an optical fiber design for
compensating an optical fiber having a center
wavelength and a substrate having a coefficient of
thermal expansion,
manufacturing an optical fiber having a long-
period grating fabricated using the calculated optical
fiber design,

attaching the fabricated optical fiber to a
support member at a first attachment point and at a
second attachment point.

5   12.   A method of compensating an optical fiber
comprising:

providing an optical fiber,
attaching the optical fiber at a first
10   attachment point and at a second attachment point, and
increasing the distance between the first
attachment point and the second attachment point in
response to an increase in temperature.

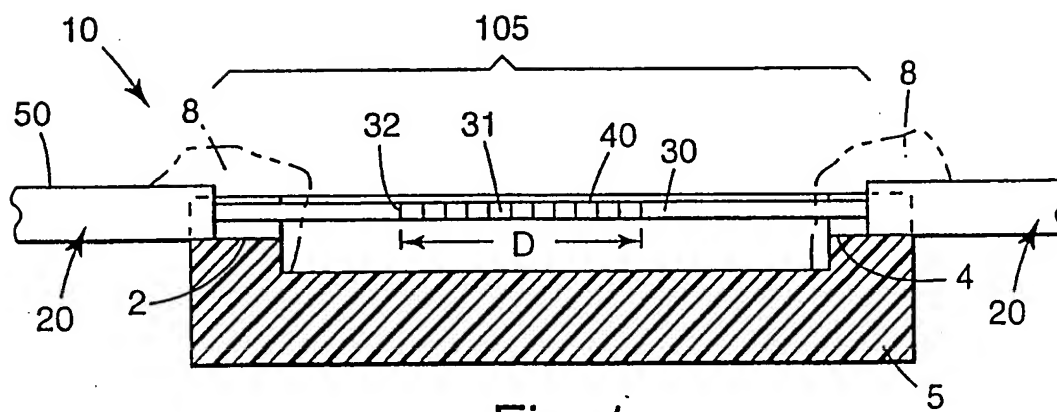15   13.   The method of claim 12, wherein the
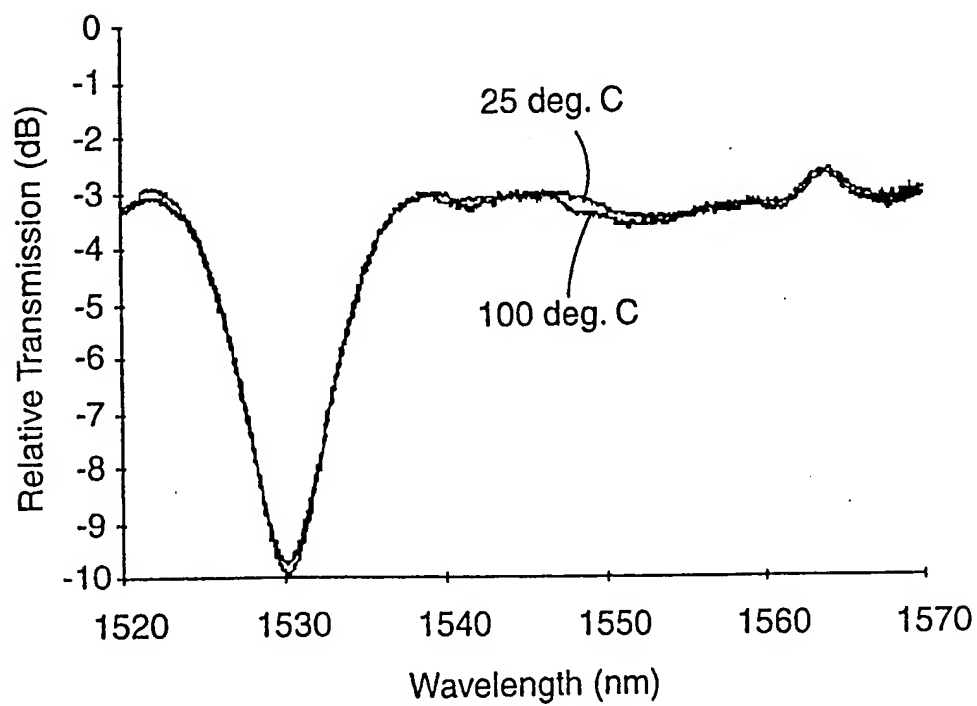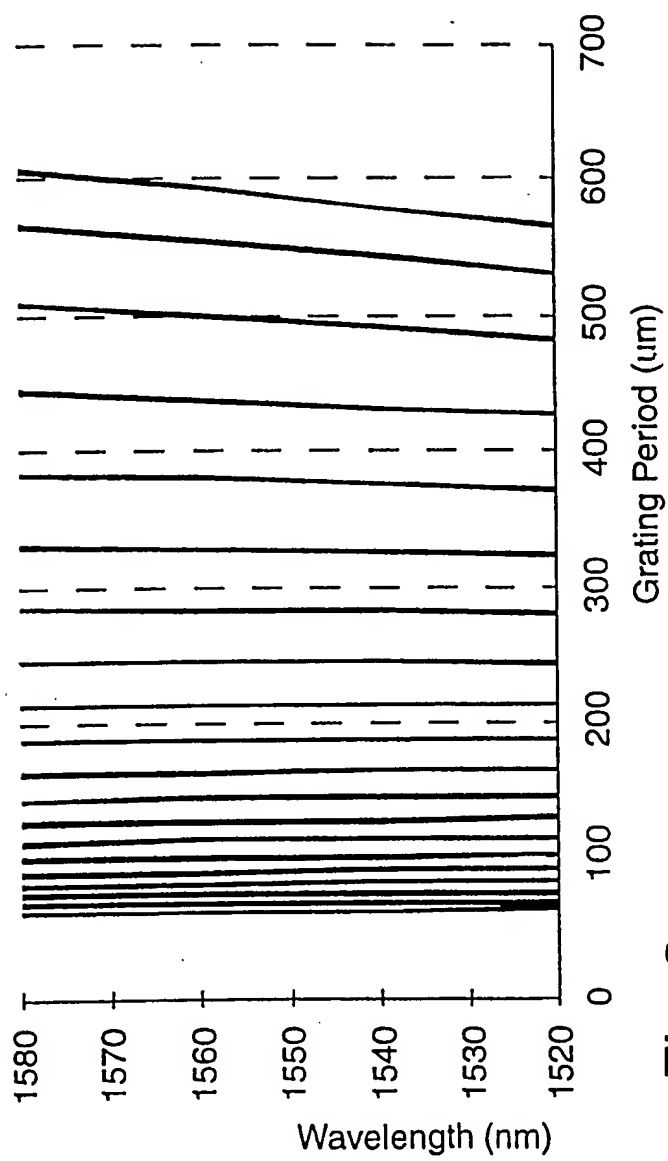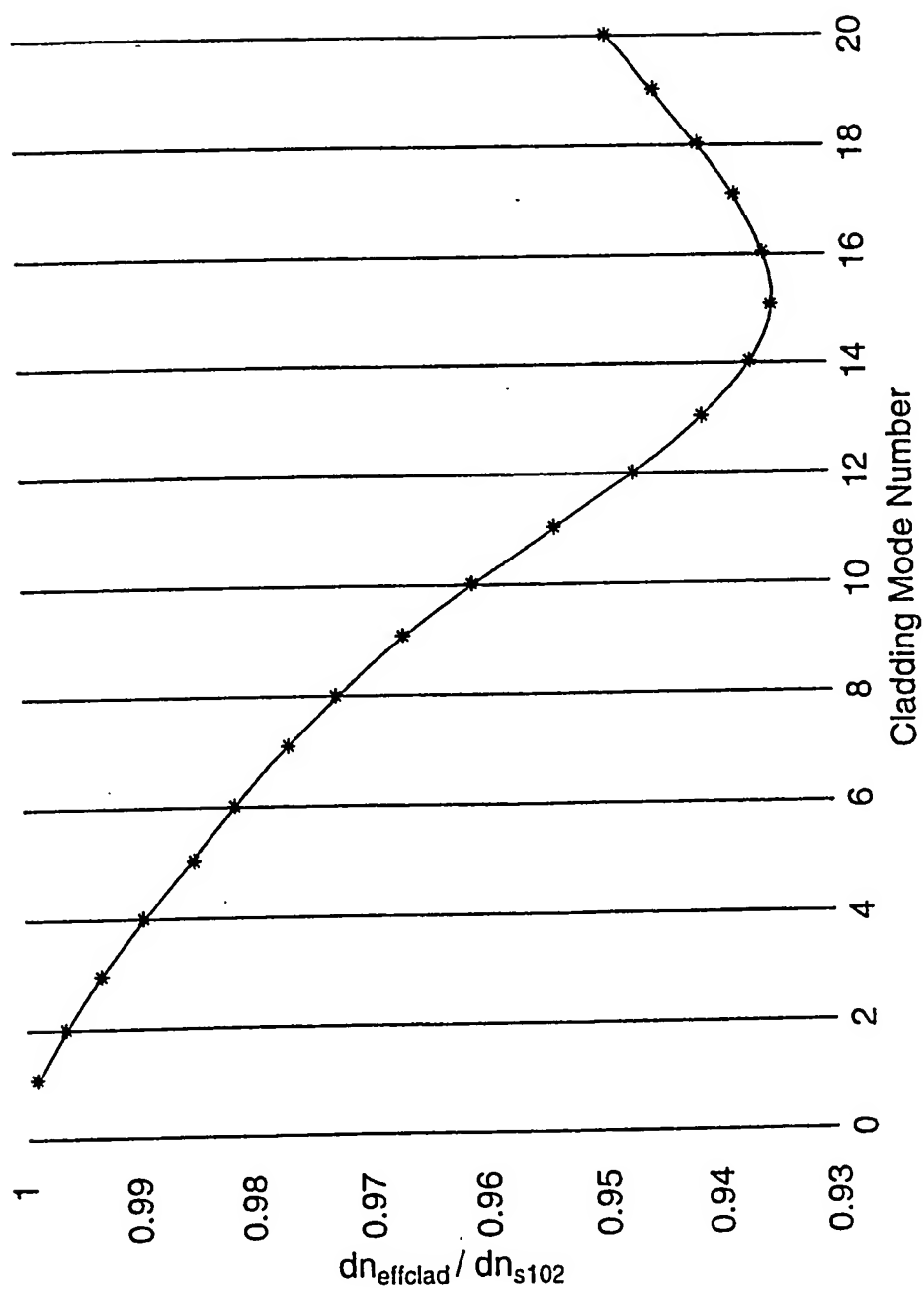compensation is done passively.

Fig. 1

Fig. 2

Fig. 3

Wavelength (nm)

Grating Period (um)

Fig. 4

INTERNATIONAL SEARCH REPORT

A. CLASSIFICATION OF SUBJECT MATTER
IPC 6   G02B6/293   G02B6/34   G02B6/14

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

IPC 6   G02B   H01S

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category°	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 5 042 898 A (MOREY WILLIAM W ET AL) 27 August 1991 see the whole document ---	1-3, 8-10,12, 13
A	WO 97 28480 A (CORNING INC) 7 August 1997 see page 1, line 24 - line 25 see page 2, line 1 - line 31 see page 3, line 1 - line 16 see page 9, line 28 - line 31 see page 10, line 1 - line 31 see page 11, line 1 - line 31 see figures 1-4 --- -/--	1,5,6, 8-10,12, 13

[X] Further documents are listed in the continuation of box C.   [X] Patent family members are listed in annex.

° Special categories of cited documents :

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier document but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
23 November 1998	18. 02. 99

| Name and mailing address of the ISA
 European Patent Office, P.B. 5818 Patentlaan 2
 NL - 2280 HV Rijswijk
 Tel. (+31-70) 340-2040, Tx. 31 651 epo nl,
 Fax: (+31-70) 340-3016 | Authorized officer

 MATHYSSEK K. |

INTERNATIONAL SEARCH REPORT

C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	YOFFE G W ET AL: "TEMPERATURE-COMPENSATED OPTICAL-FIBER BRAGG GRATINGS" OPTICAL FIBER COMMUNICATION. SUMMARIES OF PAPERS PRESENTED AT THE CONFERENCE OFC '95, SAN DIEGO, FEB. 26 - MAR. 3, 1995, February 1995, page 134/135 XP000613097 INSTITUTE OF ELECTRICAL AND ELECTRONICS ENGINEERS see the whole document ---	1-3,5, 10,12,13
A	US 5 703 978 A (DIGIOVANNI DAVID JOHN ET AL) 30 December 1997 see claims; figure 1 -----	1,7,8, 10,12

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INTERNATIONAL SEARCH REPORT

Box I   Observations where certain claims were found unsearchable (Continuation of Item 1 of first sheet)

This International Search Report has not been established in respect of certain claims under Article 17(2)(a) for the following reasons:

1. ☐ Claims Nos.:
because they relate to subject matter not required to be searched by this Authority, namely:

2. ☐ Claims Nos.:
because they relate to parts of the International Application that do not comply with the prescribed requirements to such an extent that no meaningful International Search can be carried out, specifically:

3. ☐ Claims Nos.:
because they are dependent claims and are not drafted in accordance with the second and third sentences of Rule 6.4(a).

Box II   Observations where unity of invention is lacking (Continuation of Item 2 of first sheet)

This International Searching Authority found multiple inventions in this international application, as follows:

    1. CLAIMS : 1-10,12,13
    2. CLAIMS : 11

    FOR FURTHER INFORMATION PLEASE SEE FORM PCT/ISA 206 MAILED 09.12.98

1. ☐ As all required additional search fees were timely paid by the applicant, this International Search Report covers all searchable claims.

2. ☐ As all searchable claims could be searched without effort justifying an additional fee, this Authority did not invite payment of any additional fee.

3. ☐ As only some of the required additional search fees were timely paid by the applicant, this International Search Report covers only those claims for which fees were paid, specifically claims Nos.:

4. ☒ No required additional search fees were timely paid by the applicant. Consequently, this International Search Report is restricted to the invention first mentioned in the claims; it is covered by claims Nos.:

    1-10,12,13

Remark on Protest   ☐ The additional search fees were accompanied by the applicant's protest.

                           ☒ No protest accompanied the payment of additional search fees.

Form PCT/ISA/210 (continuation of first sheet (1)) (July 1992)

INTERNATIONAL SEARCH REPORT

FURTHER INFORMATION CONTINUED FROM   PCT/ISA/ 210

1. Claims: 1-10,12,13

> refer to a device und the corresponding method of passively
> compensating it comprising the steps of
> -identifying the strain response and thermal response for
> long-period grating having a central wavelength
> -choosing a support member having a coefficient of thermal
>   expension to compensate the optical fiber and
> -attaching the fiber to the support at first and second
> attachment point.

2. Claim : 11

> is directed to a method of passively compensating optical
> fiber comprising the steps
> - calculating an optical fiber design for compensating a
> fiber having long-period grating with a central wavelength
> - manufacturing the grating using the calculated fiber
> design and
> - attaching the fiber to the support at first and second
> attachment point.

INTERNATIONAL SEARCH REPORT

:mation on patent family members

Patent document cited in search report		Publication date	Patent family member(s)		Publication date
US 5042898	A	27-08-1991	DE 69020167 D		20-07-1995
			DE 69020167 T		26-10-1995
			EP 0507877 A		14-10-1992
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